

Two-qubit state sharing between N parties using only Bell pairs and Bell-measurement

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Abstract

A quantum protocol for sharing an arbitrary two-qubit state between N parties is introduced. Any of the members, can retrieve the state, only with collaboration of the other parties. We will show that in terms of resources, i.e. the number of classical bits, the number of Bell pairs shared, and also the type of measurements, our protocol is more efficient. For achieving this, we introduce the basic technique of secure passing of an unknown two qubit state among a sequence of parties, none of which can retrieve the state without authorization of the sender and the other members of the group.

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1 Introduction

The problem of secure sharing of an unknown quantum state between two parties [1, 2, 3, 4, 5, 6], is an important one in quantum cryptography, the branch of quantum information science which uses quantum correlations between distant parties for establishing cryptographic keys and splitting and sharing information between different parties (For recent reviews see [7, 8, 9] and references therein). The security of all these protocols are based not on mathematical theorems, but on the very foundations of quantum mechanical laws, where any attempt of eavesdropping can be detected by affecting the quantum correlations between legitimate parties.

The first protocol for sharing a quantum state between two parties, was suggested in [1], where a GHZ [10] state of the form

$$|GHZ\rangle = \frac{1}{\sqrt{2}}(|000\rangle + |111\rangle), \quad (1)$$

is shared between the sender Alice and the receivers Bob and Charlie. For sending an unknown qubit state $|q\rangle := a|0\rangle + b|1\rangle$, Alice makes a Bell measurement on this and his share of the GHZ state, obtaining one of the four possible results. She then announces the result of her measurement in the form of two classical bits and asks either Bob or Charlie to perform a measurement on their share in the X basis and announce their results. The other party who has done no measurement can now retrieve the state by a suitable unitary operation. The fact that it is Alice who determines who is to receive the final state and who should do measurement in the X basis, guarantees the security of the protocol against the cheating of both the receivers.

While there is straightforward way to generalize this protocol for sharing a qubit to an arbitrary number of receivers, it is far from obvious how to generalize this protocol in the other direction, that is, sending a two-qubit state to two or an arbitrary number of parties. It is true that the original scheme of [1] can be directly generalized for sharing of arbitrary d -level states, simply by generalizing Bell states and Pauli operators in a straightforward way [11] [12], however such generalization require physical implementation of d -level states or qudits, while the mainstream candidates for implementation of quantum information processing are based on two-level states or qubits. Therefore it is essential to generalize these and any other protocol for quantum information to higher dimensional states which represent not the state of a single quantum entity (like a qudit), but that of a few quantum objects (photons, ions,...) or qubits.

It seems that for increasing the number of receivers or the dimension of the state which is to be sent, there is no other way other than using multi-party entangled states, like GHZ states and their generalization. For example in [6] a scheme has been proposed for sharing a two-qubit state between two parties, where the sender Alice shares two Bell pairs with Bob and Charlie. The pattern of Bell state sharing and measurements is shown in figure (1). To send the two qubit state (shown with red square boxes) to Charlie, she makes two GHZ measurements on her shares and the two qubit state which is to be sent and publicly announces the results of

these two measurements. Then Bob makes a product measurement $\sigma_x \otimes \sigma_x$ on his qubits, and publicly announces his result. A direct calculation then shows that Charlie can retrieve the original state after performing a suitable unitary operation, determined by the results of public bits announced by Alice and Bob.

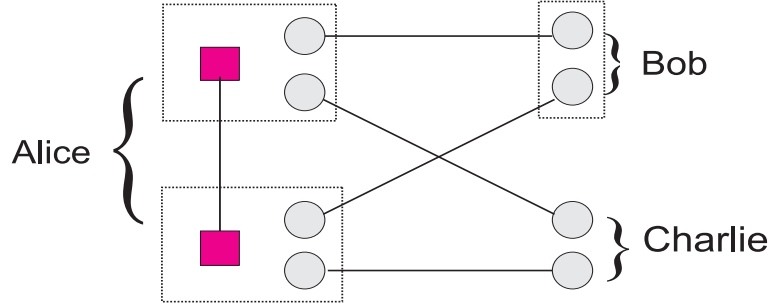


Figure 1: The pattern of Bell state sharing and measurements in the protocol of [6]. The light gray bulbs indicate Bell pairs and the red square boxes show the two-qubit state which is to be shared. The dotted boxes show the GHZ measurements which Alice has to perform and the two qubit product measurement by Bob.

Generalization of this protocol for sending a two-qubit state to N receivers [6], shown in figure (2), requires $2N$ Bell pairs and two N -qubit GHZ measurements, which is a formidable resource, especially with regard to the GHZ measurements.

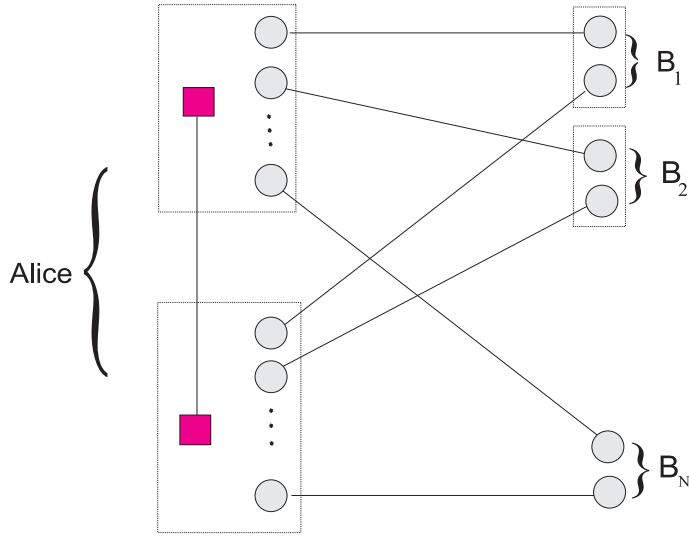


Figure 2: The pattern of Bell state sharing and measurements in the protocol of [6] for N -parties. The conventions are the same as in figure (1). However now Alice has to perform generalized measurements of GHZ types.

In this paper we want to present an alternative scheme for this kind of state sharing which uses only Bell states and Bell measurements. The motivation of this work is clear, since con-

struction, distribution and maintenance of GHZ states and their generalized N-party states and also performing measurements in such bases, are much more difficult than that of two party entangled states. In fact many of the experimental obstacles in dealing with pairs of entangled states has already been removed and it is now well known that experimental realization of quantum key distribution [13] [14], and quantum teleportation [15] has been achieved over increasingly long distances.

We will show that it is possible to securely share a two-qubit state with an arbitrary number of receivers so that only one of the members will be able to retrieve the state with the help of the other members. We will first demonstrate this for two receivers and then generalize it to N receivers. For this later part, we introduce a technique which enables the members to pass the two-qubit state one by one, among themselves, without any one of them being able to discover the identity of the state. The essence of our method is a combination of teleportation and the passing technique mentioned above. In addition to alleviating the need for using GHZ states, we will also show that our protocol requires much less classical bits to be announced publicly by the members.

For definiteness, we call the final member who is to receive the state, the receiver and the other members whose collaboration are necessary for the receiver to reconstruct the state, simply as controllers. Like the original scheme of Buzek, Berthiaume and Hillery, the security of the protocol against cheating of any subgroup of the members is guaranteed by the fact that it is Alice, the sender who decides who is to be the receiver among the members.

A remark is in order with regard to our method of presentation and reasoning. Usually secret sharing schemes, specially between N-parties, require writing many party states with lots of indices and following how these states change or collapse under different kinds of measurements which even make the notation and the presentation even more clumsy. Instead of this, we use a transparent graphical method whose correspondence with the states and their change is represented in section (2). After that we will use extensively this correspondence and use diagrams to present our reasoning and results in sections (3) and (4). Also we discuss about cheating and the number of resources in section (5) and (6). We conclude the paper with a discussion.

2 Two-qubit state sharing between two parties

Usually secret sharing schemes, specially between N-parties, require writing many party states with lots of indices and following how these states change or collapse under different kinds of measurements. This makes the presentation cumbersome and difficult to follow. Instead of this, we use a transparent graphical method whose correspondence with the states and transformations are explained in the following.

2.1 Graphical notation

In this section, we briefly remind the teleportation scheme and set up our graphical conventions. The four Bell pairs are denoted by $\{\phi_{\mu,\nu}, \mu, \nu = 0, 1\}$ where

$$|\phi_{\mu,\nu}\rangle := \frac{1}{\sqrt{2}} \sum_k (-1)^{\mu k} |k, k + \nu\rangle, \quad (2)$$

inversion of which yields

$$|m, n\rangle := \frac{1}{\sqrt{2}} \sum_{\mu} (-1)^{\mu m} |\phi_{\mu, m+n}\rangle. \quad (3)$$

Let Alice and Bob share a Bell pair of the form $|\phi_{\mu,\nu}\rangle$ and suppose that Alice wants to teleport a qubit (q) in an unknown state $|\chi\rangle = \sum_m a_m |m\rangle$ to Bob. We designate the qubits in possession of Alice and Bob respectively by the subscripts a and b . In figure (3), the Bell pair is shown the two gray-colored bulbs joined by a line with a label μ, ν and the state is shown by a red-colored square box. The total state of (qab) will be in the form

$$|\Psi\rangle_{qab} = |\chi\rangle_q |\phi_{\mu,\nu}\rangle_{ab} = \frac{1}{\sqrt{2}} \sum_{m,k} (-1)^{\mu k} a_m |m, k\rangle_{qa} |k + \nu\rangle_b. \quad (4)$$

Using (3) and rearranging terms, we find that this state can be rewritten as

$$|\Psi\rangle_{qab} = \frac{1}{2} \sum_{\mu', \nu'} (-1)^{\mu' \nu'} |\phi_{\mu', \nu'}\rangle_{qa} (X^{\nu+\nu'} Z^{\mu+\mu'} |\chi\rangle_b). \quad (5)$$

Therefore, the Bell measurement of Alice, performed on the qubits a and q , will project these two qubits onto one of the Bell pairs $\phi_{\mu'\nu'}$ and the qubit b of Bob to the state $U|\chi\rangle$, where $U = Z^{\mu+\mu'} X^{\nu+\nu'}$ and X and Z are Pauli matrices, $Z = |0\rangle\langle 0| - |1\rangle\langle 1|$ and $X = |0\rangle\langle 1| + |1\rangle\langle 0|$.



Figure 3: Teleportation of an unknown qubit χ . The retrieval operator $U = Z^{\mu+\mu'} X^{\nu+\nu'}$ depends on the initial Bell pair $\mu\nu$ and the result $\mu'\nu'$ of Alice's measurement, represented by the dashed box.

Upon public announcement of the result of Alice's measurement, that is the pair of indices (μ', ν') , Bob can recover the state $|\chi\rangle$ by the action of the operator U . This process is shown in figure (3), where a Bell pair $|\phi_{\mu\nu}\rangle$ is shown by two gray circles joined by a line on it with the label

$\mu\nu$ and the unknown state $|\chi\rangle$ with a small red square. The rectangular dotted box, indicates the measurement of Alice. We will use these conventions in all the subsequent discussions and diagram. It is important to note that even if the qubit q is in a mixed state, i.e. if it is part of larger pure state, the above diagram is still true. To see this suppose that the qubit q is a part of a two partite system qq' whose state can be written as

$$|\Phi\rangle = \sum_i |\chi_i\rangle \otimes |\phi_i\rangle. \quad (6)$$

Since the teleportation scheme in figure (3) does not depend on the state which is to be sent, this means that the outcome of the protocol will be given by

$$|\Psi\rangle = \sum_i (U|\chi_i\rangle) \otimes |\phi_i\rangle = (U \otimes I)|\Phi\rangle. \quad (7)$$

Therefore this basic diagram can be used not only when the qubit is in a pure states, but also when it is part of a larger multipartite state. When working with two-qubit states which generically are not symmetric, we denote them graphically by an arrow, where the arrow goes from the first qubit to the second qubit. We will use this fact extensively in the following discussion and diagrams.

2.2 Sharing of a two-qubit states between two parties

We can use the teleportation scheme of the last section to show that Alice can share a two-qubit state

$$|\chi\rangle_{1,2} = \sum_{i,j} K_{ij} |ij\rangle, \quad (8)$$

with Bob and Charlie so that only one of them can retrieve the information by the collaboration of the other. The pattern of Bell pair sharing and order of measurements are shown in figure 4. Alice shares one pair (a_1, b) with Bob and another identical (a_2, c) with Charlie, who in turn share a pair (b', c') between themselves. Without loss of generality, we assume all the EPR pairs to be of the form $|\phi_{00}\rangle := \frac{1}{\sqrt{2}}|00\rangle = |11\rangle$. Alice makes two Bell measurements on the qubits in her possession, namely $(1, a_1)$ and $(2, a_2)$. In this way she projects these two qubits onto two Bell states, say $\phi_{\mu,i}$ and $\phi_{\nu,j}$ respectively. From Eq. (5), the state $|\chi\rangle$ modified by the operator

$$\Omega = Z^\mu X^i \otimes Z^\nu X^j$$

is transferred to the qubits b and c in possession of Bob and Charlie. This is shown in the first part of figure (4). At this stage the retrieval operator Ω is not known to any of them, since Alice can defer her public announcement of the result to a later stage. Even if she announces her results, neither Bob nor Charlie, can retrieve the whole state, since none of them has access to both the qubits. In case that Alice wants Charlie to be the final owner of the two-qubit state, she asks Bob to perform a measurement and publicly announces his result. The two qubits will

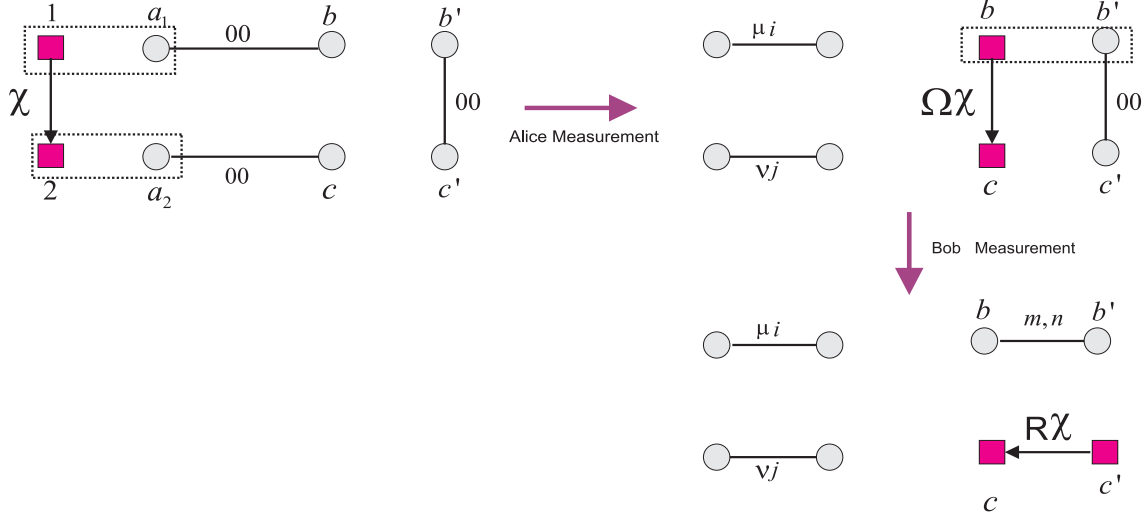


Figure 4: Sharing of a two qubit state between Bob and Charlie by Alice. Alice holds the qubits (a_1, a_2) , Bob holds (b, b') and Charlie holds (c, c') . After measurements by Alice and Bob, the state is transferred to Charlie, who can recover it by the operator R , only with the collaboration of Alice and Bob.

now be transferred to Charlie who after Alice's public announcement of her results (μ, i) and (ν, j) , can completely recover the state $|\chi\rangle$ by the action of the operator

$$R := (I \otimes Z^m X^n)(Z^\mu X^i \otimes Z^\nu X^j)_{cc'}. \quad (9)$$

Note that at the end the two Bell pairs will remain between Alice, Bob and Charlie who can use them for the next round.

3 Two-qubit state sharing between N parties

The method presented above, for splitting a two-qubit state and sending it to two parties, can be extended to the general N-party case. The essential point is to distribute the Bell pairs between the parties according to a special pattern, shown in figure (5). Each of the members except the first two, holds one share of two Bell pairs, but with two different members. No two members of the group share two complete Bell pairs. For example the member B_3 shares a Bell pair with B_1 and another one with B_5 . This scheme of Bell pair sharing, as we will show, allows all the members to pass a two-qubit state one by one from the beginning of the chain to the end, without any member being able to decipher the identity of the state. Here we assume that the final member of the group, B_N is the one who is going to recover the state, once the other members of the group B_1, B_2, \dots, B_{N-1} , i.e. the controllers, collaborate with him or her by publicly announcing the results of their measurements. This explains the difference of Bell-sharing of him or her with the other members. Also since Alice feeds the unknown state

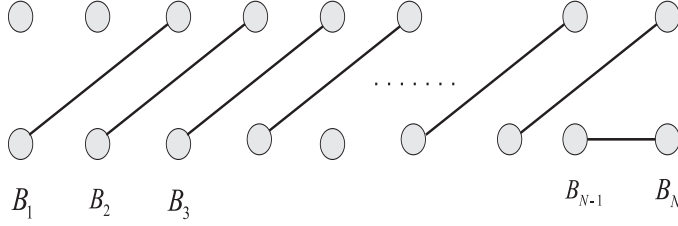


Figure 5: The pattern of Bell pairs shared between N parties B_1, B_2, \dots, B_N . Except the first two (B_1, B_2) and the last two (B_{N-1}, B_N) any member B_i shares two Bell pairs with his or her next-nearest neighbors. No two members of the group share two complete Bell pairs. Note that all the Bell pairs are of the form ϕ_{00} . We have not written the labels 00 on them.

to the left hand side of the chain, that is to B_1 and B_2 , they have a different scheme of Bell pair sharing. In later subsections we will discuss how Alice can demand that a different member acts as the receiver and hence secure the protocol against cheating. But before going into these issues, let us first describe the protocol itself which runs as follows.

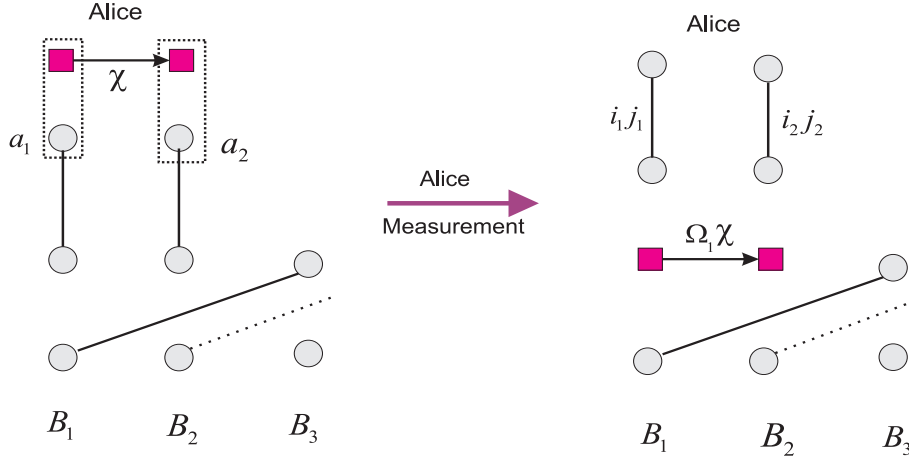


Figure 6: Step one: Alice feeds the state $|\chi\rangle_{1,2}$ to the controllers B_1 and B_2 who will pass their share to their next nearest neighbors one by one to the end of the chain. At this stage the state $|\chi\rangle$ can be recovered by the action of the operator $\Omega_1 = Z^{i_1} X^{j_1} \otimes Z^{i_2} X^{j_2}$.

The scheme consists of three major steps, which we may call i) feeding the state to the chain by Alice, ii) passing the state by controllers, and iii) retrieval of the state by the receiver. These three steps are shown respectively in figures (6), (7) and (8).

Alice first follows the steps of the previous section and teleports the state $|\chi\rangle$ to the left hand side of the chain, that is to B_1 and B_2 . This is shown in figure (6). Once fed into the chain, the controller B_1 can proceed along the same procedure and teleport his share of the state to B_3 . Now the state is shared between B_2 and B_3 . Upon continuing this process, the state is transferred one by one along the chain, until at the end it reaches the controller B_{N-1}

and the receiver B_N . A typical intermediate step is shown in figure (7). In each step note that the basic rule of transformation of the diagram is the one displayed in figure (3).

The operator which will recover the original state is $\Omega_1 = Z^{i_1} X^{j_1} \otimes Z^{i_2} X^{j_2}$. In the next step, the controller B_2 will teleport his share to the the next nearest member B_4 , which will cause the state to be shared between B_3 and B_4 . This process continues to the end, until the state reaches the last controller B_{N-1} and the receiver B_N . At each step say the $k - th$ step, when the controller B_k makes a Bell measurement with the result (m_k, n_k) , the state in transfer gains an extra correction operator

$$U_k = (I \otimes Z^{m_k} X^{n_k}),$$

leading to the recovery operator

$$\Omega_{k+1} = U_{k+1} \Omega_k.$$

Therefore when the state reaches the last controller B_{N-2} it has gained the unitary operator Ω_{N-2} (figure 8). His measurement will pass the state entirely to the receiver B_N , figure (8) with a further correction Ω_{N-1} . The receiver can now retrieve the state by the action of the correction operator

$$R = \Omega_{N-1} = (Z^{i_1} X^{j_1} \otimes Z^{i_2} X^{j_2})(I \otimes Z^{m_1+m_2+\dots+m_{N-1}} X^{n_1+n_2+\dots+n_{N-1}}). \quad (10)$$

The correction operator depends on the four bits (i_1, i_2, j_1, j_2) announced by Alice and the $2(N-2)$ bits $(m_1, n_1; m_2, n_2; \dots m_{N-1}, n_{N-1})$ announced by the controllers.

After this step, if one of them makes a measurement on his own qubits; he passes his qubit's context to his next neighbor. If all of the members keep on this algorithm and exchange their information with each other, figure 6, and finally the receiver can regenerate the initial state only with acting an appropriate operator. However non of the controllers can extract all the information; because each of them in each step has one part of the state χ , so their density matrices are in the mixed state. It is clear that in the last step, the pattern of passing is the same as two parties scheme completely, figure 4.

4 Changing the receiver

At first sight it appears that the pattern of Bell pair sharing shown in figure (5) already fixes who is to be the receiver of the state among the members of the group, and therefore Alice as the sender of the state has no choice in demanding that a different member of the group be the final receiver of the state. However this pattern can easily be changed to other desirable patterns by simple entanglement swapping. Therefore if we change the order of measurements of the members of the group, we can choose anyone of the members to act as the receiver and the other ones as controllers. This exchange which is achieved by a sequence of entanglement

swapping, can be demanded before or after step one, namely the feeding of the state into the chain. The explicit process is that Alice announces the order of measurements that the members of the group have to perform. In the process of these measurements, the identity of the members as controllers or the receiver will be established.

5 Security against cheating

How this protocol is protected against cheating of probable dishonest members? If we look at figure (7), we note that any two consecutive members of the group, say B_{k+1} and B_{k+2} in that figure, may conspire to retrieve the state by their own, hence cutting off the transfer of state down the chain. To do this, they need to share another independent Bell pair between themselves and then use the protocol described in section (3) to teleport the state to only one of them say B_{k+2} . In this way and by their own collaboration they can definitely retrieve the state $\Omega_{k+1}\chi$ which otherwise, could have been transferred down the chain. In this way they have effectively been able to cut the flow of state by cutting off the chain. However in order to retrieve the original state $|\chi\rangle$, they need to know the operator Ω which depends on all the results of previous controllers and also that of Alice. Therefore Alice can defer announcement of her results and also demands that all the controllers announce the results of their measurements only after the state has passed through all the chain. One may argue that the two dishonest parties, can proceed as described above, keep the state $\Omega_{k+1}\chi$ and send a fake qubit down the line and then wait until all announcements are made, and then recover the true state. This possibility is not ruled out, although it requires that the two dishonest members be located in adjacent positions of the chain which has after all a low probability. However, by comparing a random subset of the received state with the ones sent by Alice, she and the legitimate receiver can easily detect whether or not if there are dishonest members in the group. Furthermore by entanglement swapping a few times and hence changing the receiver and the controllers randomly, she can not only decrease the role of any cheating, but she can also detect exactly the location of dishonest members.

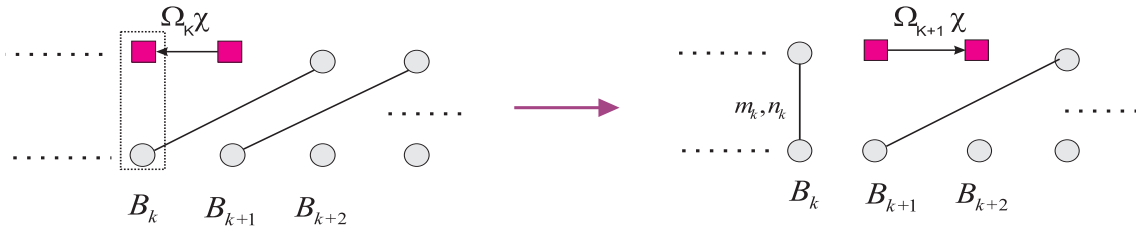


Figure 7: Step two: Passing of the state along the chain. The controllers pass the state one to the other. Here the controllers (B_k, B_{k+1}) pass the state to (B_{k+1}, B_{k+2}) . For this B_k makes a Bell-measurement, shown with the dotted box, with the random result m_k, n_k , leaving his two qubits in a state ϕ_{m_k, n_k} , and teleporting his share to B_{k+2} .

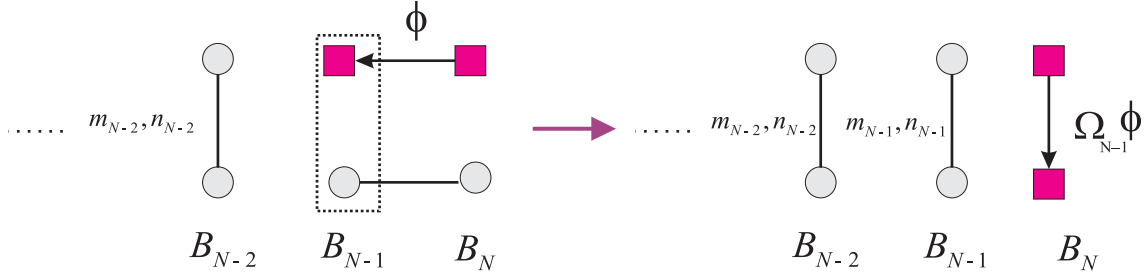


Figure 8: Step three, the final step of the protocol. The final controller passes the unknown state χ to the receiver who retrieve it with the operator R , determined by the code announced by Alice and all the controllers.

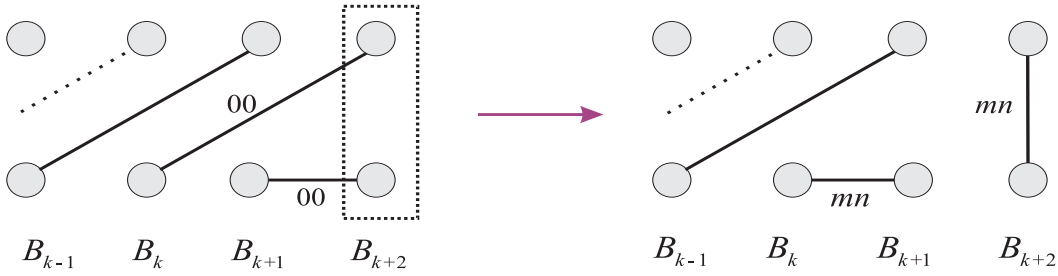


Figure 9: The exchange of the receiver and any of the controllers can be achieved by entanglement swapping. Here B_{k+1} and B_{k+2} exchange their role, B_{k+2} becomes a controller and B_{k+1} becomes the receiver. By a sequence of entanglement swapping demanded by Alice, any change of pattern can be induced.

6 A comparative account of necessary resources

In this section we make a comparison between the resources necessary for our protocol with that of ([6]). Consider the two-qubit state sharing scheme of [6] with N members (1 receiver and $N-1$ controllers). Figure (2), shows the necessary resources. It requires $2N$ Bell pairs and two measurements by Alice in the $N + 1$ qubit GHZ basis. Furthermore to announce the results of Alice's measurements, she needs to announce $2(N + 1)$ classical bits and the controllers require to announce in total $2(N - 1)$ bits.

In contrast, as explained in the text and figures (5, 6), our scheme requires, for the same number of members, the following resources: First it requires $N + 1$ Bell pairs. Furthermore it requires no measurement in the GHZ basis. Alice and the controllers require to announce $2(N + 1)$ classical bits. Table (6) summarizes this comparison.

	The scheme of [6]	our scheme
Number of Bell pairs	$2N$	$N+1$
GHZ measurements	2	0
Number of classical bits announced by Alice	$2(N+1)$	4
Number of classical bits announced by the controllers	$2(N-1)$	$2(N-1)$

Table 1: Comparison of the resources necessary for two-qubit state sharing between N members.

7 conclusion

In this article, we have introduced a more efficient and secure protocol for quantum state sharing of a two-qubit state between a group of N members. All the members of the group and the sender should collaborate with each other so that only one member called the receiver can retrieve the state after receiving classical bits from the sender and the controllers. The basic ingredient of the scheme is what we call Passing, where the state is passed through a chain of Bell pairs hold by the controllers, none of whom can detect the identity of the state, but whose collaboration is necessary for the final retrieval of the state by the final receiver. Passing of the state along the chain is achieved by a sequence of entanglement swapping. We also discuss the security of the protocol against cheating of the members of the group and make a comparison of the resources necessary for this state sharing with the one given in [6], which is summarized in table 6. We hope that the basic idea of state- passing introduced in this paper can find more applications in other applications and can be implemented in real experiments.

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